THE BEHAVIOUR OF PRE-DAMAGED REINFORCED CONCRETE STRUCTURAL SYSTEMS IN FIRE

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ABSTRACT :

It is known that when severe earthquakes occur, major fires often follow in the damaged structures. In the post-earthquake scenario fires cannot be dealt with effectively and greatly weakened structures need to be able to sustain fire loads. For design of structures in seismic regions separate fire and earthquake codes are used and complied with. Each allows some structural damage to occur but aims to prevent collapse in case of a major event. The compound situation of a fire following an earthquake is almost never considered in the design process. This study investigates the behaviour of damaged structural systems subjected to fire loads. Results show that the response to fire loading of damaged components is significantly different from those that are not pre-damaged. Pre-damage not only alters the magnitude of the response quantities but also their profile (e.g. shift in the location of the maximum response).

KEYWORDS: Reinforced concrete, frame structure, elevated temperature, plastic strain, nonlinear analysis

1. INTRODUCTION

Earthquake and fire are two extreme events in which the former is very likely to be followed by the latter. There have been a plethora of studies to examine the response of structures subjected to earthquake loading or fire loading. This study considers the response of a simple structural system subjected to an earthquake followed by fire. A single storey reinforced concrete portal frame is used for analytical demonstration. The analysis is conducted using the finite element package Abaqus. Both material and geometric nonlinearities are included in the models. Continuum plasticity is used to model post-elastic behaviour and damage. Damage due to earthquake is induced using static procedures. Fire loading is modelled by applying a temperature increase directly to the nodes of the model and both a constant temperature increase and a thermal gradient are included to more realistically model what occurs in concrete structures in fire. The aim of the study is to examine the response qualitatively rather than seek quantitative answers.

2. THE TEST STRUCTURE AND MATERIAL MODEL

The test structure used is shown in Fig. 1. The frame has a bay width of 5m and a height of 3m, while the columns have cross-section dimensions of 0.4m by 0.4m and the beam at the top is 0.3m deep and 0.2m wide. The columns were assumed fixed at the base. The finite element model used 2-noded linear beam elements. Each column is meshed using two elements, while the beam contains four elements along its span. Main reinforcement in the columns comprises 4 bars of 16mm diameter. The tension and compression reinforcement in the beam comprise 2 bars of 25mm and 2 bars of 16mm respectively. Steel and concrete are included explicitly in the model. Concrete is modelled using the concrete damaged plasticity model available in Abaqus. The yield criterion is pressure sensitive and based on the work by Lubliner et al. (1989) and Lee and Fenves (1998). For modeling reinforcement von Mises yield criterion is employed. For concrete it is assumed that the uniaxial tensile strength is one tenth uniaxial compressive strength and the post yield behaviour is perfectly plastic at any given temperature. Reinforcement is assumed to be perfectly plastic as well. In order to partly conform to Eurocode 2 (1996) on structural fire design both Young's modulus and yield stress are assumed to decrease with increasing temperature.

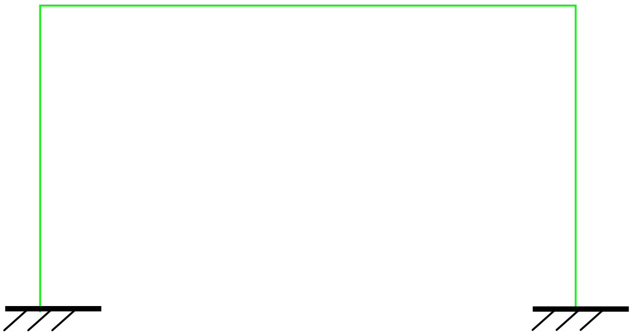


Figure 1: The test structure

3. APPLIED LOADINGS

Two forms of extreme loadings are considered. The first is earthquake loading, in the form of a lateral displacement controlled push of 0.15m applied at the beam level. This loading is considered in two forms: a push in one direction and its removal, and a push in one direction followed by load reversal and then load removal.

The second form of loading is fire loading, which is applied only to the nodes of the beam in this study. A constant temperature increase of 365.5°C is applied at mid-depth, and a temperature gradient of -2.3°C/mm is applied across the beam's depth. An exponential fire curve given by the equation

$$T_f = 20.0 + (T_{max} - 20.0) \times (1 - \exp((t \times q)) \qquad (3.1)$$

was used to find the concrete temperatures for the base and top of the beam in a 900°C fire after 60 minutes. In the above equation T_f is the fire temperature at the current time, T_{max} is the maximum fire temperature achieved, t is the current time and q is the cooling rate of the fire. These temperatures were then used to calculate the linear thermal gradient over the depth of the beam. Realistically the temperature gradient would not be constant over the depth of the beam due to concrete's low thermal conductivity – the temperature would decrease rapidly on moving away from the surface at the base of the beam.

4. FIRE LOADING ONLY

Consider the frame being subjected to the fire loading alone, as described above. If static loads (dead and imposed) are ignored then the deflected shape of the test structure is obtained as shown in Fig. 2.

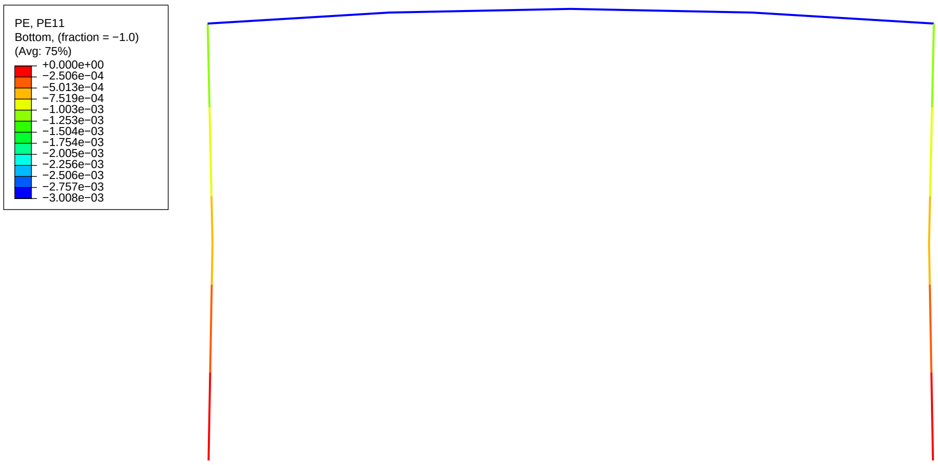


Figure 2: Deformed shape under fire loading only (magnification x200)

It can be seen that in spite of the temperature gradient which should cause bowing downwards in the beam, joint rotation due to the constant temperature increase causes upward bowing. This thermal loading is sufficient to cause inelastic deformation in the structure. Plastic strain is almost constant along the beam span and decreases to zero at the fixed ends of the columns. The beam is in compression along its length, caused by the constant temperature increase at its mid-depth.

A realistic uniformly distributed load (which is included in all subsequent analyses) was then included, and fire loading was applied to the structure. The resulting deformed shape and consequent plastic strains are shown in Fig. 3. It is noted that upward bowing is not apparent here and that the UDL has confined the largest plastic strains to the central elements of the beam. Both the UDL and the thermal gradient cause tension at the base of the beam; whereas a constant temperature increase induces compression and causes joint rotation at the ends of the beam. This reduces the amount of thermal bowing downwards. It is important to note that for reinforced concrete structures thermal gradient is likely to dominate the response of the structure, particularly in short, hot fires, due to the poor thermal conductivity of concrete.

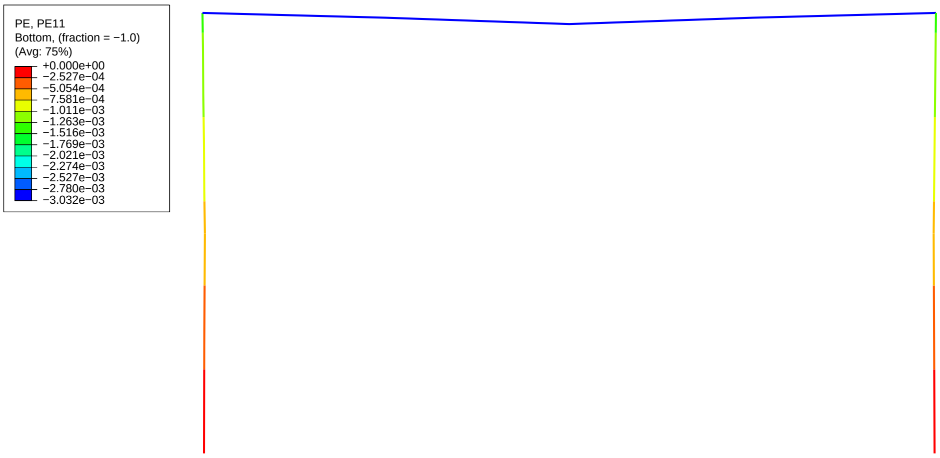


Figure 3: Deformed shape under UDL and fire loading (magnification x200)

5. EARTHQUAKE AND FIRE LOADING

Consider the application of earthquake loading (in the form of a push) in one direction, its removal and application of fire loading as discussed above. The load – horizontal deformation (at the point of load application) graph is shown in Fig. 4. The resulting deformed shapes with plastic strains are shown in Fig. 5.

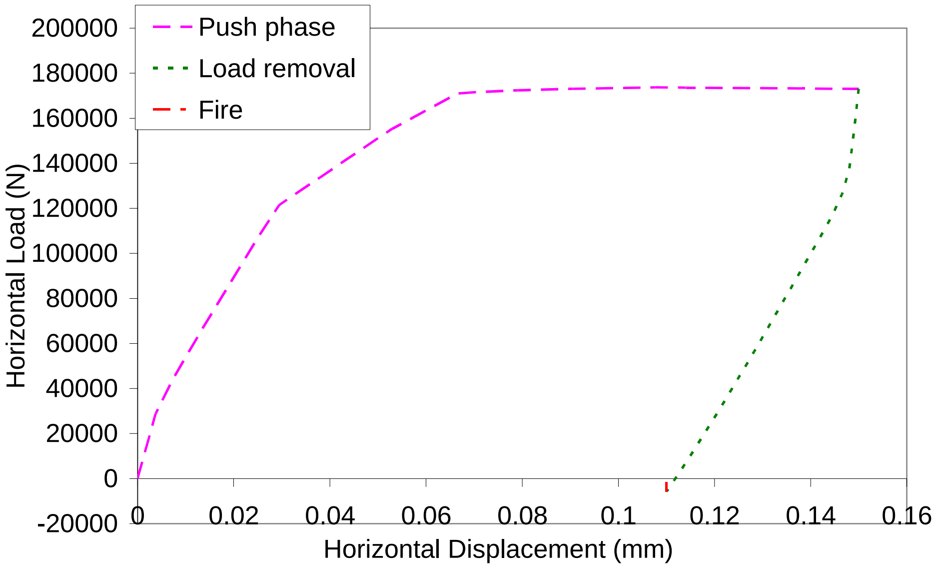
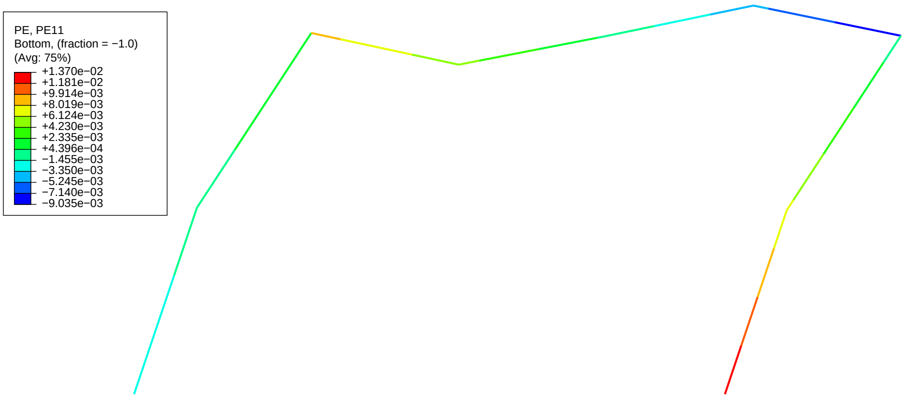


Figure 4: Load – Horizontal Deformation (at the point of load application)

It can be seen that the lateral load causes the largest compressive plastic strains to occur at the right end of the beam and the largest tensile plastic strains at the bottom end of the right column (see Fig. 5a). The tensile plastic strain at the left end of the beam is larger in magnitude than the compression found at the right; this is due to lower tensile yield strength. Load removal causes the structure to displace leftwards (Fig 5b); this can also be seen in Fig. 4. However, the plastic strain profile and the deformed shape are not significantly altered.



(a)

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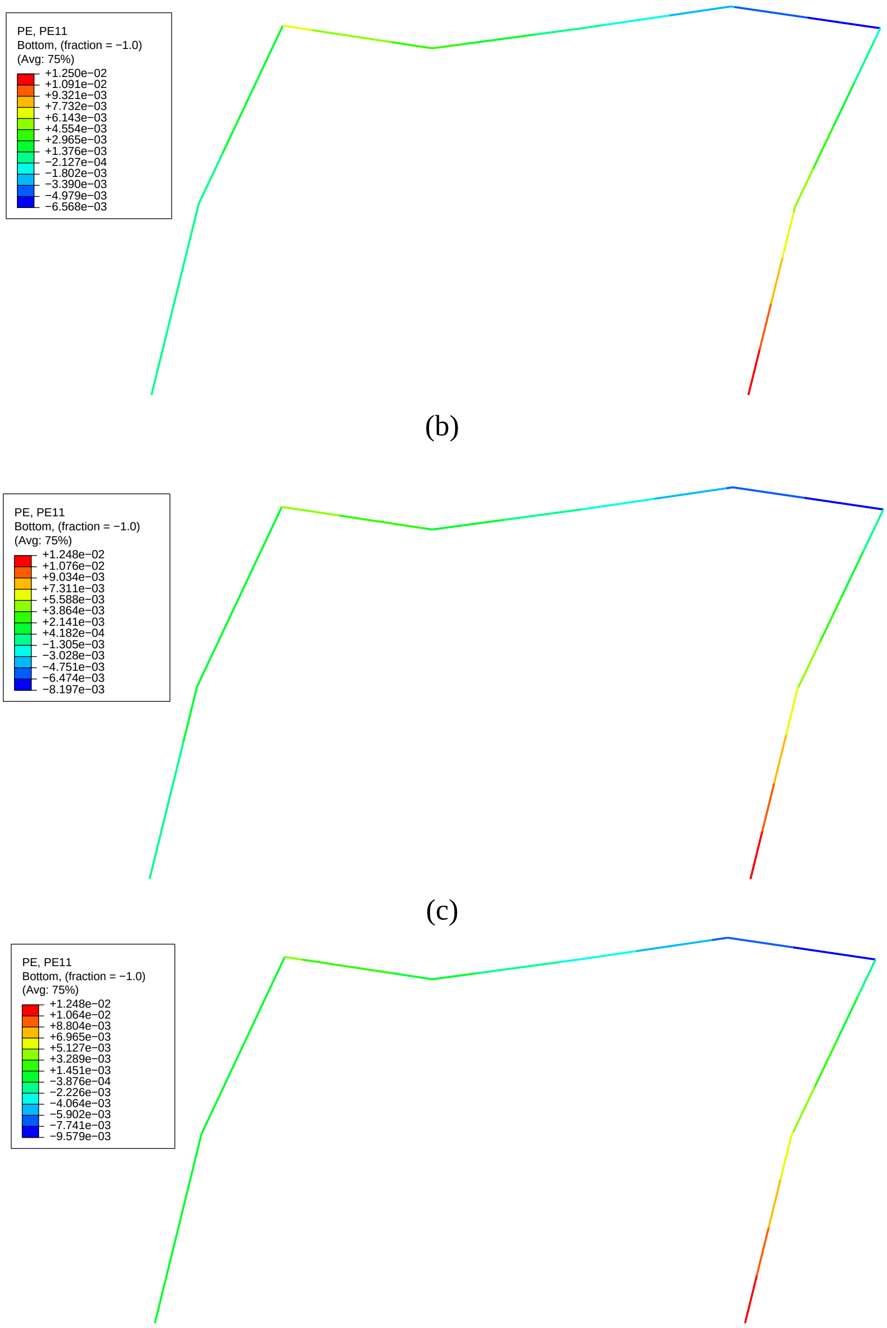


(b)

(c)

(d)

Figure 5: Deformed shape (magnification x10) after:
(a) Push to the right, (b) Load removal, (c) 60% of fire loading, (d) End of fire step

Figures 5c and d are for the fire application step. Figure 5c shows the structure after 60% of fire load has been applied and Fig. 5d is the response after complete application of the fire loading. From these figures it is seen that there is no change in the maximum tensile plastic strains found at the base of the right column. Meanwhile, in the beam, the compressive strains (at the right side) increase over the fire step, while the tensile strains (at the left side) decrease. This is due to expansion of the beam, due to the constant temperature increase, causing compression.

Now consider the application of loading as: push in one direction, followed by load reversal, load removal and finally application of fire load. The load-deformation plot is shown in Fig. 6.

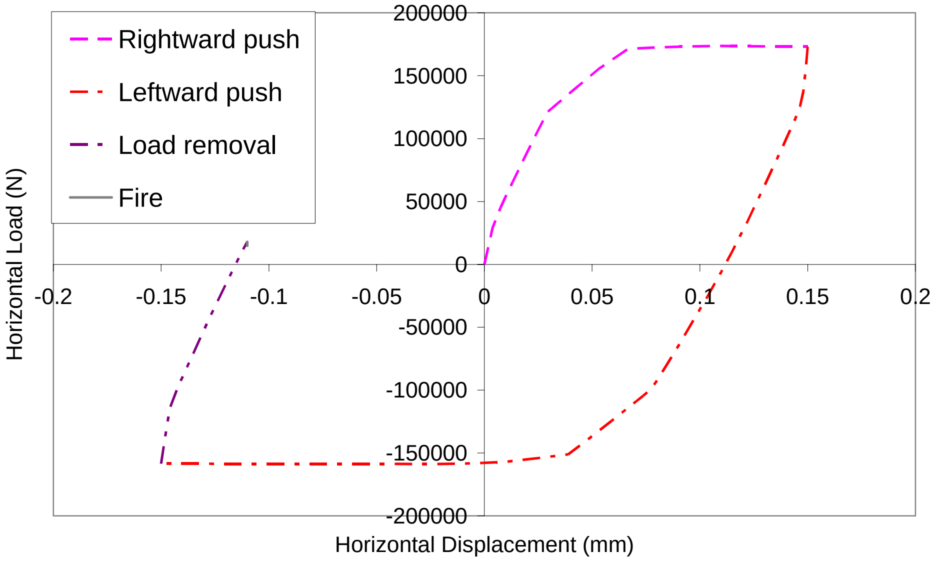
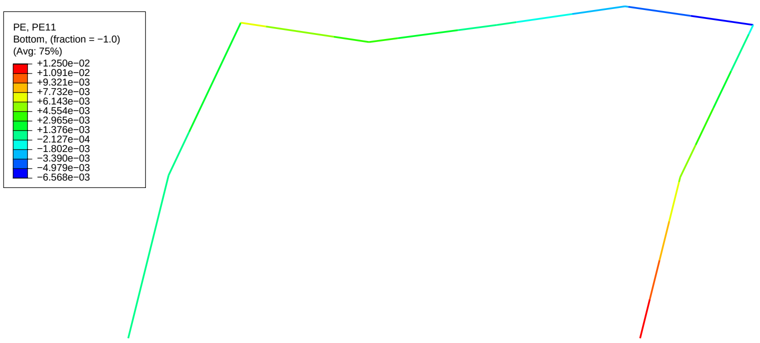


Figure 6: Load – Horizontal Deformation (at the point of load application)

The development of deformation and principal plastic strains is shown in Fig. 7. Figure 7a is identical to Fig. 5b and shows the response when the load applied rightwards is removed. Figure 7b is the response when load has been applied in the leftward direction. It can be seen that load reversal leads to all plastic deformation becoming tensile. Figure 7c is of deformation after load removal, when it is seen that all plastic strains remain tensile. Once again this causes elastic recovery, but overall deformation now is towards the left. Figures 7d and 7e show the development of the fire loading response. As in Fig. 5 there is no change in the tensile strains found at the base of the left column (where maximum tension occurs). Throughout the beam, the value of tensile plastic strains present decreases as fire loading increases, both where the value is relatively large (the right side) and where it is smaller (the left side). Again, this is due to the expansion of the beam with constant temperature increase, causing compression.



(a)

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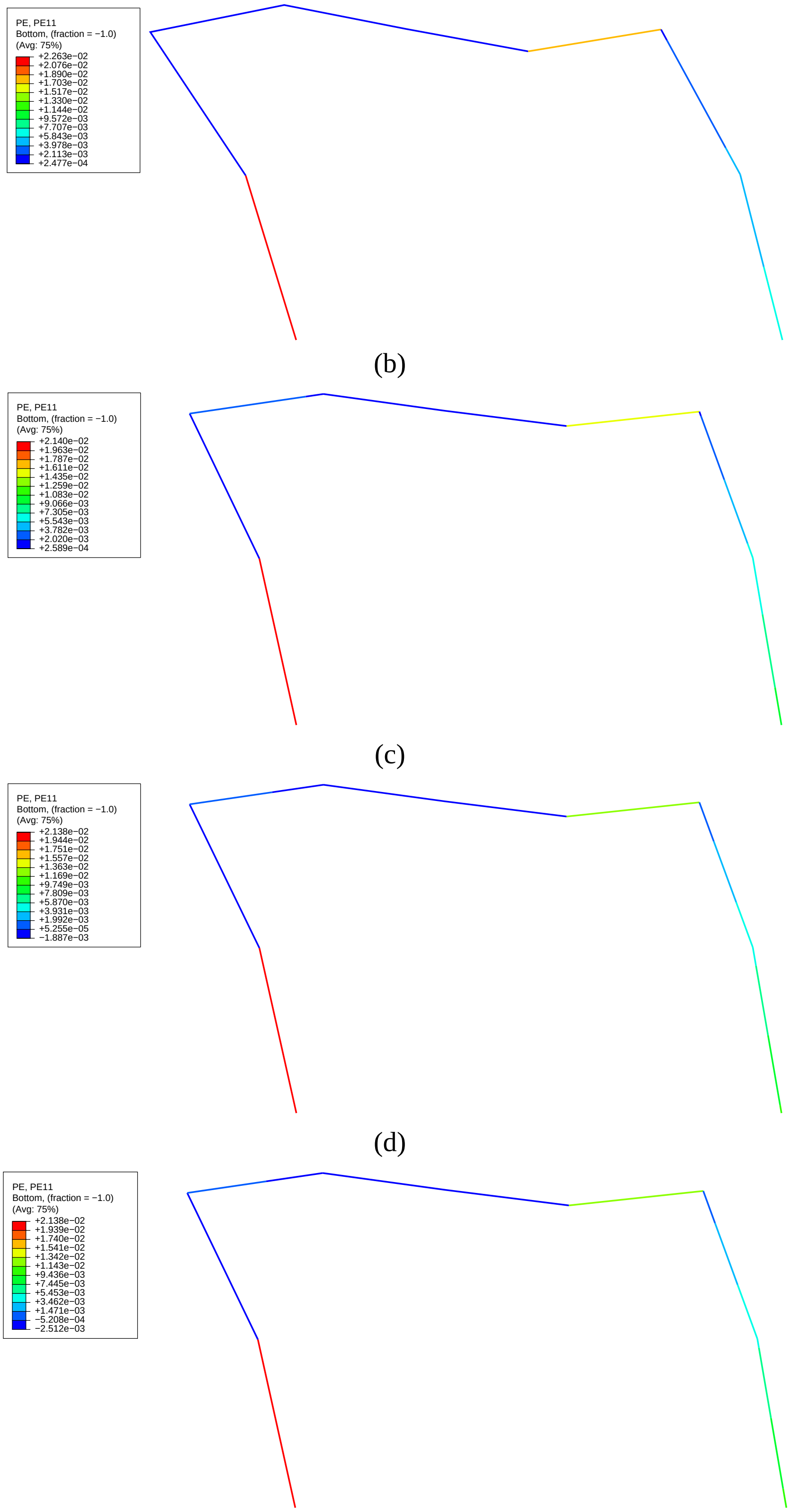

(b)

(c)

(d)

(e)

Figure 7: Deformed shape (magnification x10) after:
(a) Removal of rightward push, (b) Leftward push, (c) Load removal, (d) 80% of fire loading, (e) End of fire step

6. CONCLUSIONS

It has been shown that fire loading causes plastic strains to be distributed in the beam. Column rotation acts against temperature gradient and uniformly distributed load, preventing or limiting downward thermal bowing. Further research needs to consider more realistic thermal gradients and the effect when temperature loading is applied to columns as well as to the beam.

Fire loading of the beam after application of seismic forces appears to have little effect on the columns. It induces compressive strains in the beam, thereby increasing compressive or reducing tensile plastic strains.

Application of seismic forces causing plastic damage changes the behaviour of the structure under fire loading – instead of symmetrical compressive plastic strains being induced, areas of varying tensile and compressive strain are caused within the beam.

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